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Economic injury levels for *Bemisia tabaci* (Homoptera: Aleyrodidae) in cotton: impact of crop price, control costs, and efficacy of control

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Field studies were conducted during 1993 and 1994 in the Imperial Valley, California and Maricopa, Arizona to examine relationships between densities of *Bemisia tabaci* (Gennadius) populations and cotton (*Gossypium hirsutum* L.) yields, and to estimate economic injury levels (EILs) for pest management application. Populations of *B. tabaci* were manipulated by applying different numbers of insecticide applications in replicated plots. Resulting insect populations and cotton lint yields were used to develop damage functions and to estimate EILs for all life stages in relation to variable cotton prices, insecticide costs, and pest control efficacy. Economic injury levels declined with increasing cotton prices and increased as the cost of control increased, however, these changes were relatively small, based on typical ranges in price and control costs. In contrast, the efficacy of control provided by insecticide applications had a large influence on EILs, with lower efficacies being associated with higher injury levels. We developed a multiple regression model that accounted for the dynamic changes in the EIL in relation to crop price, control costs, control efficacy, and potential yield. Based on average prices and reasonable control costs and efficacy, EILs ranged from 5.9–15.2 adults/leaf, 6.1–19.8 eggs cm^{-2}, and 1.7–4.7 nymphs cm^{-2} of leaf area. Additional research is needed to more closely relate the costs of control to the suppression of insect populations, and to define economic thresholds that will enable pest managers to maintain pest populations below EILs. Published by Elsevier Science Ltd

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Bemisia tabaci (Gennadius) Biotype B (= *Bemisia argentifolii* Bellows and Perring) has caused large economic losses in cotton production in Arizona, California and Texas since 1991. The cotton acreage infested in the United States in 1993 and 1994 was estimated at 282,000 and 345,000 ha with yield loss of 7.7 and 3.6 million kg, respectively (Williams, 1994, 1995). Most of this damage was concentrated in Arizona and southern California. Insecticides are the principal control method at present and will probably continue to be important components of future management systems. The development of decision aids for the rational and efficient use of these insecticides is critical to extending the longevity of this important control approach, and to optimizing economic returns and minimizing environmental impacts.

The concept that pest control should be based on economic as well as ecological considerations has been a pervasive force in integrated pest management over the past 30 years (Stern, Smith, van den Bosch and Hagen, 1959). However, the development of economic injury levels (EIL), which defines the break-even point between loss due to pest damage and costs of control, and the economic thresholds, which is the operational pest density triggering control actions, has typically lagged behind their need (Poston, Pedigo and Welch, 1983; Pedigo, Hutchins and Higley, 1986). This is largely due to the difficulty of studying the dynamics of pest damage interactions and pest suppression, and the market forces driving the economics of commodity price, production costs, and costs of control.

Several operational action thresholds have been suggested and implemented for whitefly control in cotton (Ellsworth and Meade 1994; Mabbett, Nachapong and Mekdaeng, 1980; Stam, Abdelrahman and Munir, 1994; Sukhija, Butter and Singh, 1986). These thresholds are based on a combination of experience and field research with the goals of maximizing yields and/or maintaining controllable pest populations levels. These efforts have been extremely important in providing producers and pest managers with tools for rational decision-making; however, they have not explicitly incorporated the economics of loss

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and control. We conducted studies in Brawley, California and Maricopa, Arizona, USA during 1993 and 1994 to determine relationships between densities of *B. tabaci* and crop damage in cotton, and to estimate EILS in relation to variable cotton prices, costs of insecticidal control, and efficacies associated with control.

Materials and methods

Experimental studies

Deltapine 5415 cotton (*Gossypium hirsutum* L.) seed was planted and irrigated for germination on 22 March 1993 and 16 March 1994 at the Desert Irrigated Research Station, Brawley, California. Treatment regimes consisted of applying a mixture of fenpropathrin and acephate (both from Valent Corp., Walnut Creek, CA) at 0.22 and 0.56 kg AI ha^{-1}, respectively, on a weekly basis beginning on progressively later weeks through the season. The experimental design was a randomized complete block with four replications. Each plot was four rows wide and 18.3 m long with 1 m row spacings. There were four unplanted rows between plots and 9.1 m fallow alleys between blocks. The objective was to establish a range of *B. tabaci* population densities and crop damage levels. In 1993, the first set of plots was initially sprayed on 28 April and the last set of plots was initially sprayed on 7 July. In 1994, these dates were 27 April and 13 July, respectively. After the initial application, each series of plots was treated weekly until 4 August in 1993 and 27 July in 1994 for a total of 10 and 12 spray initiation dates in 1993 and 1994, respectively. Untreated plots served as controls. These treatment regimes resulted in plots sprayed 0, 5, 7, 8, 9, 10, 11, 12, 13, 14 and 15 times in 1993 and 0, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13 and 14 times in 1994. Insecticides were applied with a backpack sprayer configured with three 6002 TeeJet nozzles operated at 138 kPa and using a volume of 323 l ha^{-1}. One center nozzle was directed to the plant tops and two drops, 33 cm in length, attached 51 cm on either side of the center, were configured with drop-nozzles oriented at 45° angles to direct spray to leaf undersides. All applications were made shortly after dawn so that ambient temperature variations (minimum 16–21°C) were minimized between applications. No other pesticides were applied during the season.

Whitefly population densities were estimated weekly from 27 April to 10 August in 1993 and from 26 April to 9 August in 1994. Once insecticide applications began, sampling was conducted 24 h before each application. We randomly selected 10 fifth mainstem node leaves (counted down from the terminal) from each plot, as described by Naranjo and Flint (1994), to estimate the density of eggs and nymphs (all stages). In 1993, the density of adults was estimated using flat yellow sticky cards (7.6 × 12.7 cm) placed in each plot perpendicular to the cotton rows for a 24 h period. In 1994, adults were counted on the underside of 10 fifth mainstem node leaves per plot (Naranjo and Flint, 1995) between daybreak and 0800 h. In order to provide consistent estimates of adult density over both seasons a linear regression ($F = 142.9$, d.f. = 1, 11; $P < 0.001$; $r^2 = 0.93$) of the seasonal mean adults per leaf on seasonal mean eggs per square centimeter from the 1994 study was used to estimate the mean density of adults per leaf from the mean density of eggs in 1993.

Cotton lint yields were measured in each plot on 24 August in both years by collecting all open bolls within two 4-m lengths of row. This seed cotton was ginned and lint weights were converted to kg ha^{-1}.

Further analyses of pest density and yield relationships, and of EILs were based on seasonal mean densities of the various life stages of *B. tabaci*. In order to arrive at a rational starting point in the season for the calculation of consistent estimates of seasonal density we examined treatment effects and population patterns over time. Analysis of variance was used to examine differences in the density of insects among treatments for each sampling data using MSTAT-C (1988). In 1993, there were no significant differences between treatments in the weekly density of any insect stage until 15 June ($P > 0.05$). Likewise, in 1994 there were no significant differences between treatments until 24 May. Examination of population trends over time revealed that densities of all stages were very low for all treatments (< 0.41 eggs cm^{-2}, 0.37 nymphs cm^{-2} and < 0.15 adults per leaf) over these early periods of the season in both years. The dates of 15 June, 1993 and 24 May, 1994 marked the first time that densities of adults were ⩾ 0.5 per leaf. Because all currently recommended action thresholds for *B. tabaci* are based on adult density and generally exceed 0.5 per leaf by at least an order of magnitude. (Ellsworth and Meade, 1994; Stam *et al.*, 1994, Sukhija *et al.*, 1986), we selected this point in the season to begin averaging densities of all stages for further analyses.

Additional studies were conducted at the University of Arizona, Maricopa Agricultural Center in 1994 to estimate the control efficacy associated with a more typical number of insecticide applications and to provide data to test the robustness of the pest density–yield relationship developed at the Brawley, California site. Paired plots of Deltapine 5415 cotton, planted 15 April (0.09 ha each, 10 replications) were either treated with insecticides for *B. tabaci* or left untreated. Insecticide applications were made with a spray boom mounted on a Hi-Boy tractor. Treatment recommendations were made by the Maricopa Agricultural Center pest control advisor and were based on the adult sampling methods of Naranjo and Flint (1995) and an action threshold of about five adult whiteflies per leaf. Oxamyl (Dupont, Wilmington, DE, 0.17 kg AI ha^{-1}) was applied to all plots on 27 June for *Lygus hesperus* Knight control. Fenpropathrin plus acephate was applied 15 July, 2 August and 29 August at rates of 0.20 kg AI ha^{-1} and 0.56 kg AI ha^{-1}, respectively, for whitefly control. All plots were also sprayed with chlorpyrifos (Dow-Elanco, Indianapolis, IN; 0.22 kg AI ha^{-1}) on 10 August and oxamyl (0.71 kg AI ha^{-1}) on 29 August for cotton leafperforator, *Bucculatrix thurberiella* Busck, control. Densities of adult and immature *B. tabaci* were estimated weekly in all plots from 27 June to 29 August. Densities of adult were estimated using the black pan sampling method of Butler and Wilson (1986). Densities of eggs and nymphs were estimated from leaf disks taken from 30 fifth mainstem node leaves from each plot as described by Naranjo and Flint (1994).

Seasonal mean densities for adults, eggs and nymphs for sprayed and unsprayed treatments were calculated using the criteria presented above (begin averaging when adults per leaf ≥ 0.5). Pan counts for adults were converted to adults per leaf using the relationship between the two sampling methods reported by Naranjo, Flint and Henneberry (1995). Results were used to estimate the efficacy of control in comparison with untreated plots. Lint yields were determined by collecting all open bolls from 4 m of row in all plots on 26 September. The seed cotton was ginned and lint weights converted to kg ha^{-1}.

Economic injury level analysis

The relationship between lint yield (Y) and the seasonal mean density of eggs, nymphs or adults each year was modeled using a simple negative exponential decay relationship given by:

$$Y = Ae^{(-bn)} \tag{1}$$

where A is yield (kg ha^{-1}) when insect density (n) is zero and b is a rate parameter. Models were fitted using least-squares regressions of $\ln(Y)$ on n. In general, maximum yields were about 250 kg ha^{-1} higher in 1994 in comparison with 1993. In order to develop a single relationship between insect densities and yield across years, we scaled yields in each year in relation to maximal observed yields. We then used the following equation to model the relationship between the proportion of maximum yield and seasonal insect densities:

$$Y = MAe^{(-bn)} \tag{2}$$

where M is potential or maximum yield and A is the proportion of maximum yield when pest density is at or near zero.

Economic injury levels were estimated for adults per leaf and for eggs and nymphs (all stages combined) per cm^2 of leaf area using the method outlined in Southwood and Norton (1973). The EIL has been variously defined; however, the most functional definition is that the EIL is that density of the pest which causes damage equal to the cost of control. This can be mathematically stated as:

$$C(a) = Y[d\{n(a)\}]\,P - Y[d\{n\}]\,P \tag{3}$$

where, $C(a)$ is the cost of control a, Y is yield, d is damage, n is pest density, and P is price per unit of yield. We modeled yield here as a direct function of insect density so equation 3 simplies to:

$$C(a) = Y[n(a)]P - Y[n]P \tag{4}$$

The yield level at which the cost of control equals the yield loss prevented by implementing control is given by:

$$Y[n] = Y[n(a)] - C(a)/P \tag{5}$$

Using equation 1 for the yearly models or equation 2 for the general model, the EIL can then be estimated as the pest density associated with the yield determined in equation 5, respectively:

$$\mathrm{EIL} = \ln[Y/A]/(-b) \tag{6}$$

$$\mathrm{EIL} = \ln[(Y/A)/M]/(-b) \tag{7}$$

The use of this economic injury model requires several assumptions. First, we assume that all yield loss in our experimental plots could be attributed to damage by *B. tabaci*. This is reasonable as populations of pink bollworm, *Pectinophora gossypiella* (Saunders), the only other major pest of cotton in the Imperial Valley of California have been extremely low in recent years. Fewer than 0.01 male moths were captured in pheromone traps per night at the research site in both 1993 and 1994. Captures in nearby commercial fields have been equally low, averaging 0.25 and 0.04 in 1993 and 1994, respectively (Chu *et al.*, 1996). Second we assume that price is not influenced by damage to yield. This is reasonable because *B. tabaci* indirectly influences yield by removing assimilates from the leaf. This insect directly influences the quality of the lint through honeydew deposition; however, this affect can be accounted for in grade reduction and subsequent price discounts. Finally, we assume that yield loss can be adequately predicted by the mean seasonal density of the pest. This implies that yield loss is not influenced by the timing of infestation and subsequent feeding damage. This is a reasonable assumption in the geographic area of this study because *B. tabaci* infests cotton early in the growing cycle and persists throughout the season.

The per unit price of cotton and the per unit cost of insecticides and application are variable. Cotton prices (in \$ kg^{-1}) were \$1.61, \$1.76, and \$1.98 for 1993, 1994, and January 1995, respectively (personal communication, Paul Horton, Calcot Ltd, Imperial, CA). Assuming standard rates of 0.22 kg AI ha^{-1} for fenpropathrin and 0.56 kg AI ha^{-1} for acephate, we estimated the cost of materials as \$31.24 ha^{-1} and \$12.86 ha^{-1}, respectively (personal communication, C. R. Waegner, Rockwood Chem. Co., Brawley, CA). The cost of application was estimated at \$13.59 ha^{-1} for aerial application and \$27.18 ha^{-1} for ground application (personal communication, M. Barrett, Stoker Co., Imperial, CA). The total cost of each application was then estimated to be \$57.69 ha^{-1} by air and \$71.28 ha^{-1} by ground.

We estimated EILs for each life stage in relation to these variable control costs and cotton prices. We further examined EILs in relation to the efficacy of control provided by the varying number of insecticide application made over the course of the season in both years and by examining scenarios regarding the number of insecticide applications necessary to achieve various levels of control efficacy. Finally, because all these factors are variable, we developed a multiple regression model (SAS Institute, 1989), which allows the estimation of EILs as a function of price, control costs, efficacy, and potential yield.

Results and discussion

Pest damage and yield

Lint yields declined in a non-linear fashion with increasing mean seasonal densities of eggs, nymphs, and adults of *B. tabaci* and these relationships were reasonably well represented by a simple negative exponential model (*Figure 1*). Parameter values and coefficients of determination for these functional relationships are given in *Table 1*. In general, fits of the model were very good ($r^2 \geq 0.93$) with the exception of adults vs yields in 1994 ($r^2 = 0.78$). Overall, lint yields were higher in 1994 than in 1993, even though *B. tabaci* populations were similar in both years. The reasons for this are not clear, but it was probably related to differing agronomic and/or weather conditions between years. In order to develop a general relationship between yield and insect density we scaled yields relative to the maximum observed yield in each year. In 1993 the highest mean yield (1734 kg ha^{-1}) was in treatment plots receiving nine weekly insecticide applications. In 1994 the highest yield was 2007 kg ha^{-1}, which was in plots receiving 11 applications. The maximum yield can be thought of as the potential yield achievable with little or no pest damage. Although this variable complicates the prediction of pest damage, it is likely that many producers could estimate potential yield based on experience with cultivars, agronomic conditions, and production practices on their farm. These generalized models fit the data well (*Table 1*, *Figure 1*).

The general pattern of our damage functions could be characterized by what Pedigo *et al.* (1986) refer to as 'desensitization'. Small changes in pest abundance had a relatively large effect on yield at low densities, but changes in progressively higher populations of the pest had a diminishing effect on yield. Overall, results of our study indicate that cotton may tolerate relatively high populations of *B. tabaci* without substantial lint yield loss.

Table 1. Coefficients of negative exponential models for the relationship between densities of life stages of *B. tabaci* and lint yield (kg ha^{-1}), Brawley, California, USA

Year/Life stage	Model parameters[a] A	b	r^2
1993			
Eggs cm^{-2} leaf	1602.1	0.02034	0.93
Nymphs cm^{-2} leaf	1611.4	0.06996	0.95
Adults $leaf^{-1}$	1602.3	0.02396	0.93
1994			
Eggs cm^{-2} leaf	1912.6	0.01790	0.94
Nymphs cm^{-2} leaf	1907.9	0.08270	0.94
Adults $leaf^{-1}$	2004.4	0.02126	0.78
Combined[b]			
Eggs cm^{-2} leaf	0.94	0.01845	0.93
Nymphs cm^{-2} leaf	0.94	0.07616	0.94
Adults $leaf^{-1}$	1.00	0.02287	0.84

[a]Model for individual years given by $yield = Ae^{-bn}$, where A is yield when pest density, n, is zero, and b is a rate parameter. Combined model is given by $yield = MAe^{-bn}$, where M is maximum or potential yield, and A is the proportion of M when pest density is zero

[b]The y-axis was scaled as the proportion of maximum yield observed in each year

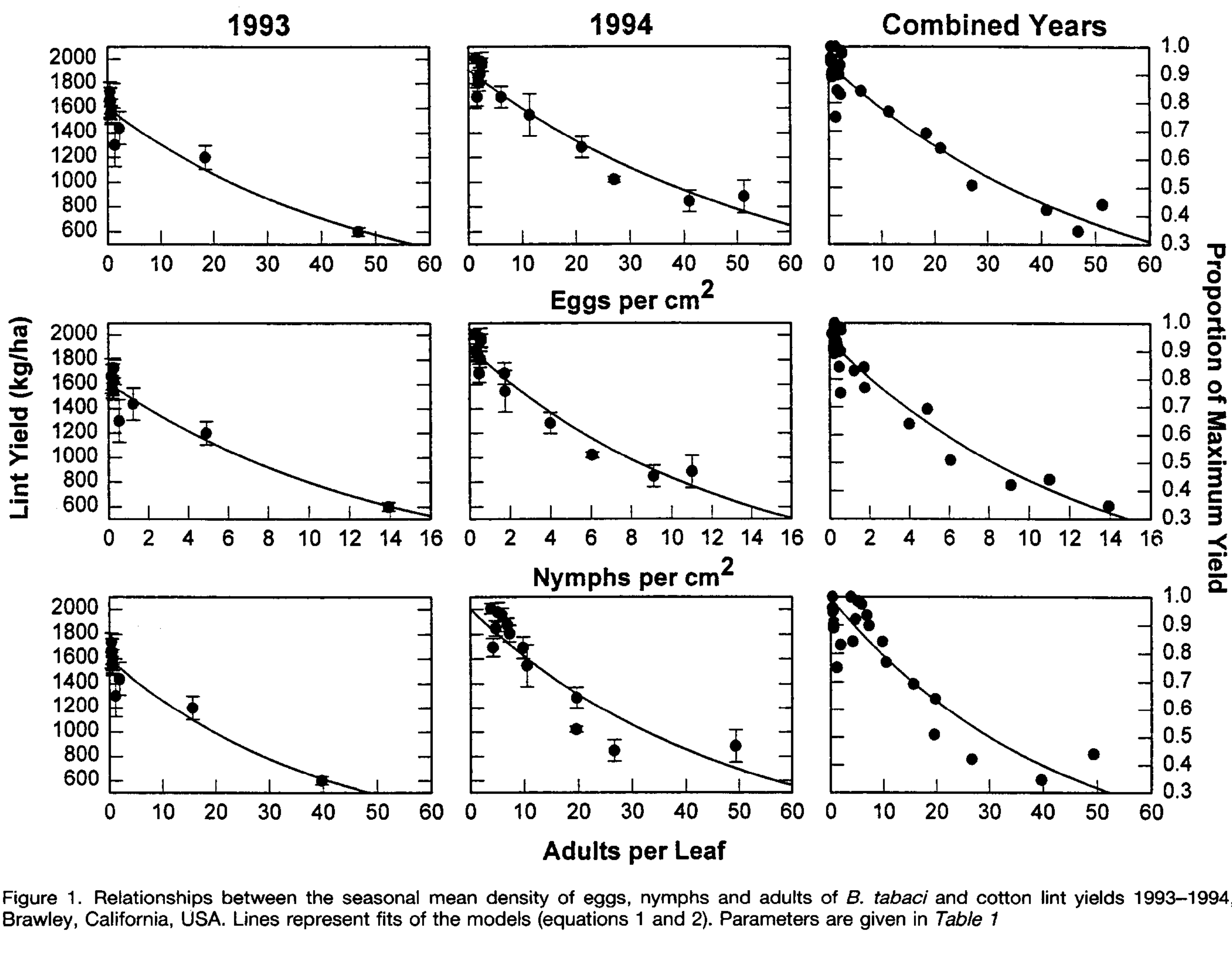

Figure 1. Relationships between the seasonal mean density of eggs, nymphs and adults of *B. tabaci* and cotton lint yields 1993–1994, Brawley, California, USA. Lines represent fits of the models (equations 1 and 2). Parameters are given in *Table 1*

The damage functions were tested against data from Maricopa, Arizona in 1994. We used the seasonal mean density of *B. tabaci* estimated in Maricopa (*Table 2*) to predict the yields we observed at this site using our generalized damage function (see *Table 1*). In order to estimate potential yield at this site we used results from another study at the Maricopa farm that used the same short-season cultivar (Flint, Naranjo, Leggett and Henneberry, 1996). In certain plots of this study *B. tabaci* populations were kept at very low levels using low action thresholds (one adult leaf^{-1}), and additional insecticides were used to control *L. hesperus* and various caterpillars. Yields in these plots averaged 1917 kg ha^{-1}. We used this figure as an estimate of potential yield at our Maricopa site. In both untreated and treated plots, predictions of yield fell within the 95% confidence interval of observed yields (*Figure 2*). The same cultivar was used at both Maricopa and Brawley sites, however, planting dates, agronomic conditions, weather, the timing of *B. tabaci* infestations, and the frequency of insecticide applications differed. Results suggest that the damage functions we developed here are relatively robust, at least for the cultivar examined. In turn, because the damage function is the most funamental component of the EIL, this also suggests that the results presented below may have relatively broad applicability to the management of this pest.

Table 2. Efficacy of control of *B. tabaci* populations and yield enhancements, Maricopa, Arizona, USA, 1994

Stage	Untreated plots	Treated plots[a]	Control efficacy	*n*
Eggs cm^{-2}	20.7 ± 5.4	2.2 ± 0.5	0.89	20
Nymphs cm^{-2}	7.8 ± 2.1	0.9 ± 0.2	0.89	20
Adults leaf^{-1}[b]	25.7 ± 4.5	5.4 ± 0.8	0.79	20
Yield (kg ha^{-1})	1210.3 ± 95.3	1697.1 ± 59.2	1.4[c]	20

Means ± SE

[a]Treated plots received insecticide applications (fenpropathrin: 0.22 kg AI ha^{-1} and acephate: 0.56 kg AI ha^{-1}) on 15 July, 2 and 29 August

[b]Counts of adults per black pan converted to adults per leaf using the regression model given by Naranjo *et al.* (1995)

[c]Relative increase in lint yields in treated plots compared with untreated plots

Economic injury levels

The EIL is not a static level because its components are dynamic. Both commodity prices and the costs of control can be highly variable. In order to examine the sensitivity of EILs for *B. tabaci* we used equation 6 to calculate EILs for reasonable estimates of lint prices and costs of control using conventional insecticides and application methods. Also, because of the structure of our experimental studies we were able to examine the sensitivity of these EILs to changes in the efficacy of control. We estimated the efficacy of each experimental treatment in each year by calculating the proportional reduction in mean seasonal insect density relative to the unsprayed control. The cost associated with this efficacy was then assumed to be the per application cost of control multiplied by the total number of applications applied for any given treatment regime. The sensitivity of EILs to combinations of these three variables; lint price, control cost, and control efficacy, are shown in *Figure 3*. Results were similar for each life stage and so only results for adults are presented here. Economic injury levels were relatively insensitive to changes in per unit control costs or changes in lint price. For any

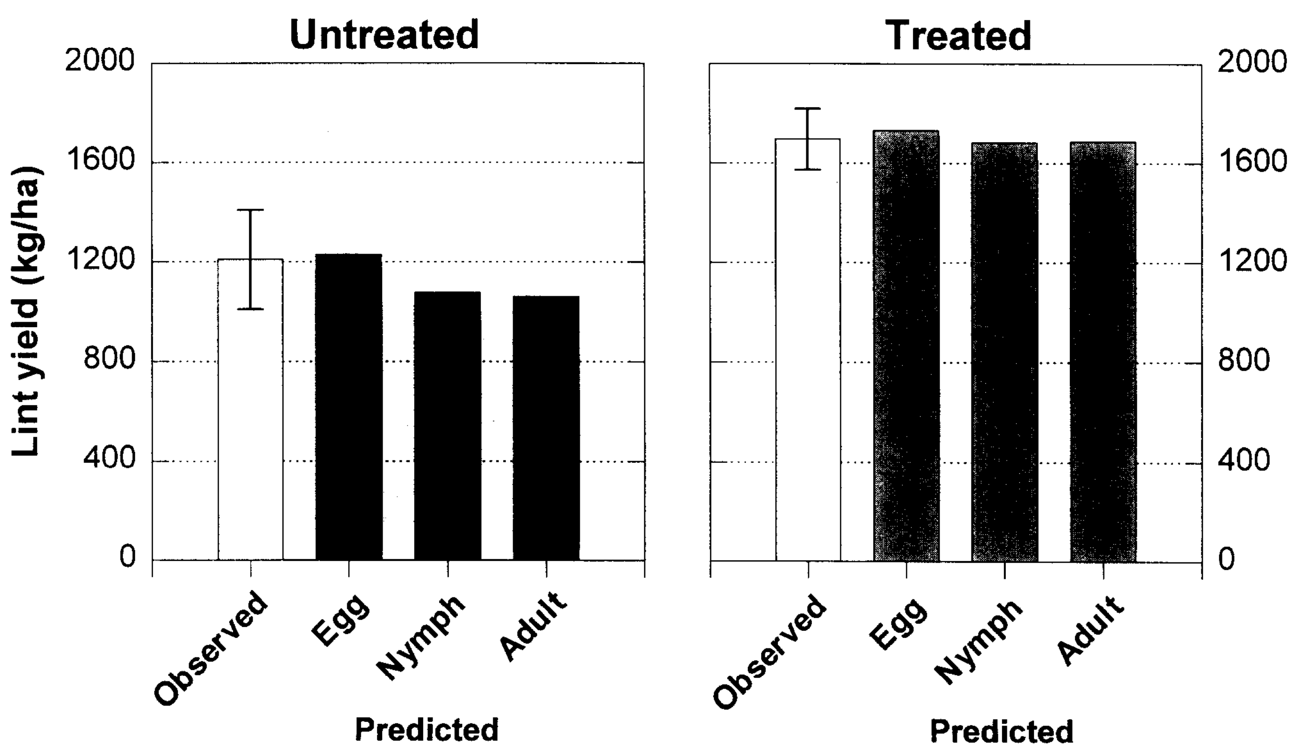

Figure 2. Comparison of yields observed at the Maricopa Agricultural Center, Maricopa, Arizona, USA, 1994 to those predicting from the combined model (equation 2, *Table 1*) using seasonal mean densities of eggs, nymphs or adults from *Table 2* and a potential yield of 1917 kg ha^{-1}. Error bars represent 95% confidence limits

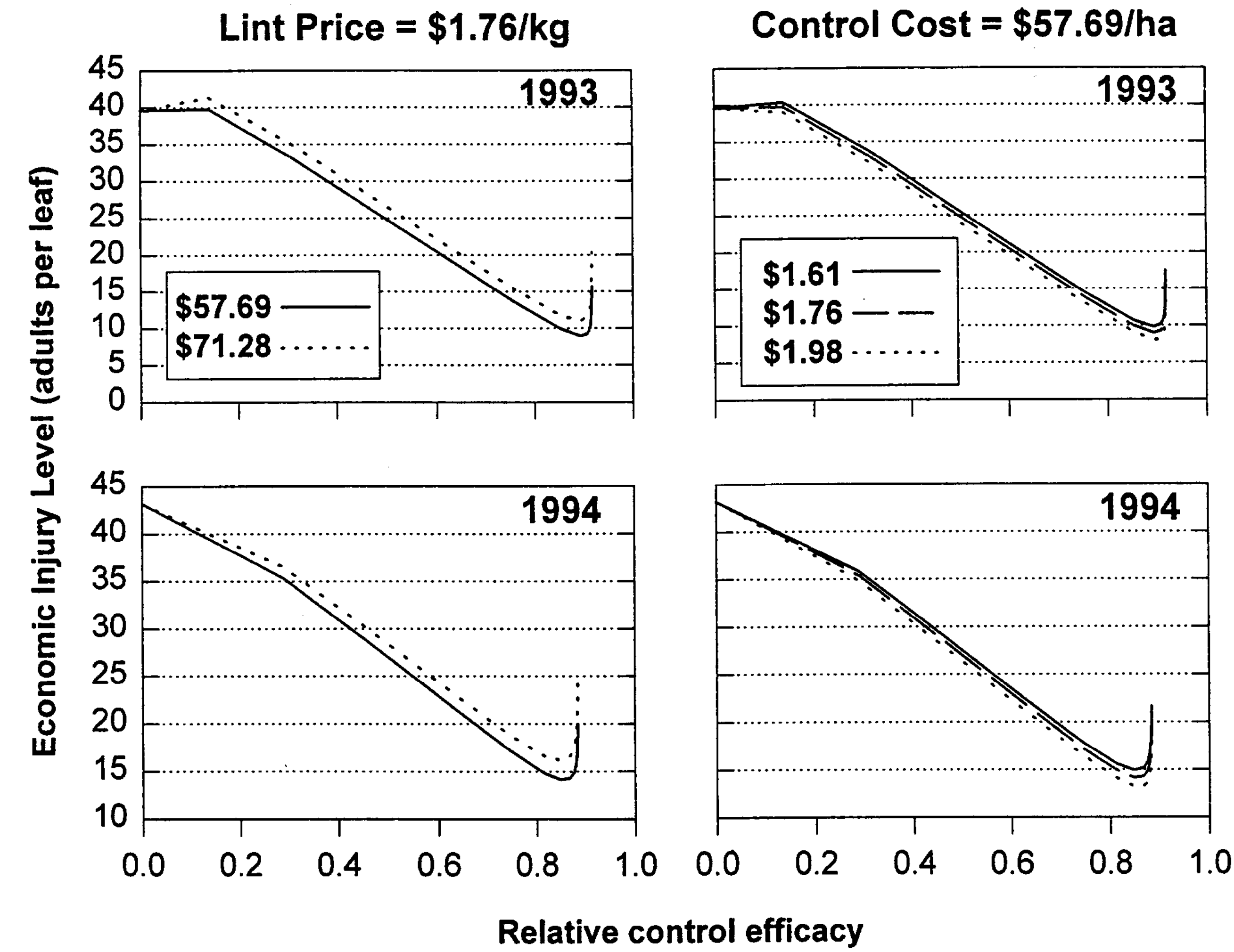

Figure 3. Economic injury levels for adult *B. tabaci* in cotton in relation to changing lint prices, control costs, and the efficacy of control, 1993–1994, Brawley, California, USA. The efficacy of control was calculated relative to populations in untreated plots. Lower control efficacies were associated with experimental treatments receiving fewer insecticide applications over the season

given efficacy, the EIL changed less than about two adults per leaf. This change is within the expected error of the sampling protocol recommended for *B. tabaci* in Arizona (Ellsworth *et al.*, 1994; Naranjo, Flint and Henneberry, 1996). In contrast, changes in the efficacy of control had a large effect on the EIL. Increasing levels of efficacy progressively reduced the EIL. This somewhat counter-intuitive result follows from the fact that the cost of control is not being offset by a corresponding gain in yield through insect suppression. Thus, because insect control is poor at low levels of efficacy, yield savings can only be economically justified if treatments are triggered by relatively high pest populations. The non-linear behavior at high values of efficacy result from the fact that additional insecticide sprays beyond about seven or eight applications had no significant effect on pest suppression ($P > 0.05$) or associated enhancements in yield ($P > 0.05$). Because we are dealing with seasonal levels of control, reduced efficacy can be viewed as a function of the use of less potent materials and/or the use of fewer applications of a potent material.

Efficacy of control appears to be a highly significant factor in influencing EILs, however, there are several limitations to the analyses presented above. First, the total costs of control for a given level of efficacy were imposed by the experimental design and may not accurately reflect the actual cost of control necessary to achieve the same efficacy. Second, it is likely that efficacies below 70% would represent unacceptable performance for an insecticide application. We performed an additional sensitivity analysis of efficacy and control costs that attempted to address these important limitations. Experimental treatments receiving fewer than six weekly insecticide applications resulted in levels of efficacy < 62% in both years and for all life stages. In contrast, the application of more than eight weekly sprays did not significantly enhance seasonal levels of pest control, which typically exceeded 90%. Thus, we focused on the efficacies associated with treatments receiving six, seven or eight weekly applications and examined sensitivities in EILs relative to the assumption that these levels of efficacy could be achieved with fewer insecticide applications (*Figure 4*). Again, results emphasized the relatively high sensitivity of EILs to total control costs and levels of efficacy. For adults, EILs decreased about five adults leaf^{-1} from the lowest to the highest efficacies, independent of control costs. Economic injury levels also increased about five to seven adults leaf^{-1} as control costs associated with a given efficacy increased, depending on year. Similar patterns were observed for EILs based on egg density (not shown) and nymphal density, although changes were smaller in magnitude for this latter life stage.

Results from this analysis (*Figure 4*) suggests that accurate determination of EILs for *B. tabaci* will require additional information on the relationship between the cost of control and efficacy. Studies conducted at the Maricopa Agricultural Center in 1994 indicate that fairly high levels of control can be achieved with relatively few, but well timed insecticide applications (*Table 2*). Although seasonal populations were roughly half of those observed in Brawley in both years, we were able to achieve control efficacies of 79% for adults and 89% for immatures in Maricopa with three applications of the same materials at similar rates, and using similar application methods. These levels of efficacy were simlar to those achieved in Brawley with six to eight weekly applications and suggest that fewer applications may have accomplished equal levels of pest control.

The sensitivity analyses presented above reinforces the variable and dynamic nature of EILs. Unlike action thresholds that are often static and are based largely on experience and expectations of maximized yield and quality, EILs explicitly integrate these factors with economic considerations to maximize profits. Because it is difficult to predict the market forces that will influence cotton prices and per unit costs of control tactics, and difficult to adequately estimate the costs associated with achieving desired levels of pest suppression in all situations, we cannot list specific EIL for *B. tabaci*. Instead, we used our EIL model (equation 6) to generate EILs for a wide range of reasonable scenarios and then used multiple regression to formulate predictive models for calculating specific EILs. The independent variables of our model include price of cotton, total cost of control, efficacy of control, and the maximum potential yield. Coefficients of models for adults/leaf, eggs cm^{-2} and nymphs cm^{-2} are presented in *Table 3*. We also estimated standardized coefficients for these models so that the relative influence of each variable could be evaluated independent of the numerical scales of the variables. Examination of standardized coefficients highlights the importance of control efficacy and the total cost of control to achieve this efficacy for

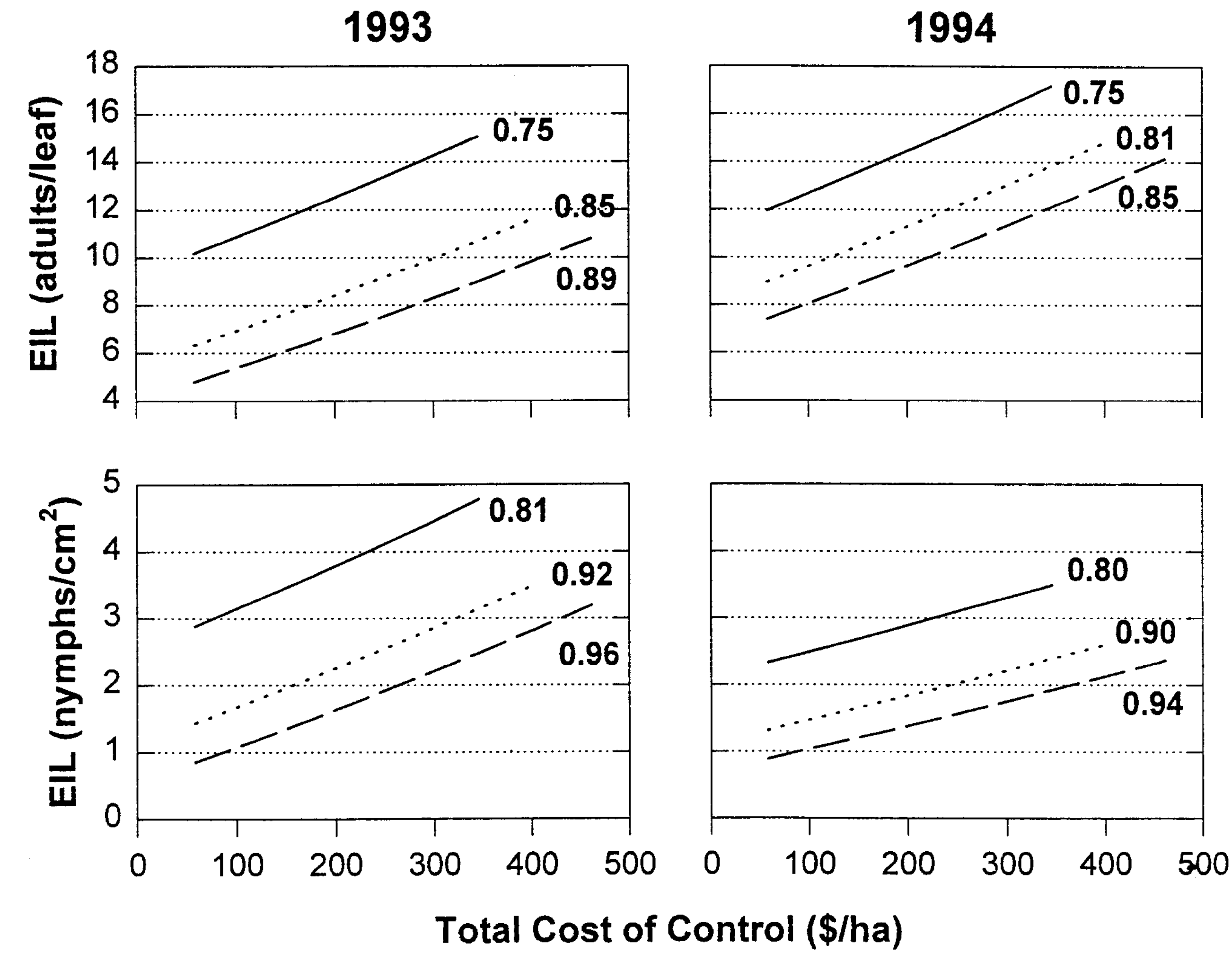

Figure 4. Economic injury levels for adults and nymphs of *B. tabaci* in cotton in relation to the efficacy of control (numbers adjacent to lines) and the total control costs associated with achieving that efficacy, 1993–1994, Brawley, California, USA. The highest costs were associated with six, seven or eight weekly applications as determined by the experimental design. Progressively lower costs were associated with the assumption that fewer, better timed applications could result in the same seasonal levels of control. Results were based on a price of \$1.76 kg^{-1} and a per unit control cost of \$57.69 ha^{-1}

Table 3. Coefficients of multiple regression models for estimating economic injury levels for *B. tabaci* in cotton

Independent variables	Regression coefficients			Standardized coefficients[a]		
	Adults leaf^{-1}	Eggs cm^{-2}	Nymphs cm^{-2}	Adults leaf^{-1}	Eggs cm^{-2}	Nymphs cm^{-2}
Intercept	59.893	74.626	17.775	0.0	0.0	0.0
Price ($ kg^{-1})	–2.278	–1.485	–0.368	–0.116	–0.058	–0.060
Total control cost ($ ha^{-1})	0.0173	0.020	0.0049	0.750	0.674	0.697
Efficacy (Proportion control)	–46.890	–48.119	–13.024	–0.827	–0.949	–0.811
Potential yield (kg ha^{-1})	–0.0054	–0.0130	–0.0023	–0.246	–0.453	–0.335
r^2	0.99	0.97	0.97	—	—	—

General form of equation: EIL = a + b(price) + c(control cost) + d(efficacy) + e(potential yield), where a, b, c, d and e are regression coefficients
[a]Standardized coefficients weight the relative contribution of each variable independent of their numerical scale

Table 4. Economic injury levels for *B. tabaci* life stages associated with various scenarios of cost of control, efficacy of control, and maximum potential yield assuming a price of $1.76 kg^{-1}. Economic injury levels were estimated using the multiple regression models presented in Table 3

Total control cost ($ ha^{-1})	Efficacy of control	Potential yield (kg ha^{-1})	Economic injury level: Adults leaf^{-1}	Eggs cm^{-2}	Nymphs cm^{-2}
173.07	0.9	1500	8.60	12.68	2.83
230.76	0.9	1500	9.59	13.86	3.12
288.45	0.9	1500	10.58	15.03	3.41
173.07	0.9	2000	5.88	6.17	1.69
230.76	0.9	2000	6.87	7.35	1.98
288.45	0.9	2000	7.87	8.52	2.27
173.07	0.8	1500	13.29	17.50	4.14
230.76	0.8	1500	14.29	18.67	4.42
288.45	0.8	1500	15.28	19.84	4.71
173.07	0.8	2000	10.58	10.99	2.99
230.76	0.8	2000	11.57	12.16	3.28
288.45	0.8	2000	12.56	13.33	3.57

estimating EILs for all life stages. In comparison, cotton price and potential yield have relatively little influence on the EIL.

These results have important implications for the management of *B. tabaci*. One of the major concerns regarding the effect of this pest is the issue of lint stickiness resulting from contamination by honeydew and associated sooty molds that affect lint processing at the textile mill (Hector and Hodkinson, 1989). Also, little effort has been expended to determine the potential effects of whitefly on other lint quality parameters such as fiber length, strength and micronaire. It is likely that these quality characteristics are adversely affected because of the severe plant stress that can result from high levels of pest infestation (Henneberry *et al.*, 1995). Although of great concern to the cotton industry, these quality factors would have minimal effects on EILs because they are adjusted for through price structures that penalize poor quality (e.g. sticky lint) and/or place a premium on high quality lint. Such discounts would be relatively unimportant in terms of economic thresholds because fairly large changes in price have little effect on EILs (see *Figure 3*, *Table 3*). Overall, insensitivity to price suggests that a single EIL could apply to all probable crop prices. Conversely, factors such as insecticide resistance (Prabhaker *et al.*, 1992) could have a major influence on increasing control costs and reducing control efficacy. Thus, insecticides with poor efficacy (due to resistance or other factors such as poor coverage) would drive the EIL up to a level at which pest control may not be economically justified even if yields were severely depressed. Thus, management strategies to delay or prevent resistance development and maintain the efficacy of existing chemistry should be a major focus of research.

We used our multiple regression equations to generate EILs for various likely scenarios (*Table 4*). We assumed aerial application methods, average cotton prices, and based on results from Maricopa, Arizona (see *Table 2*), control costs associated with three to five insecticide applications to achieve moderate to high levels of control efficacy. The lowest EILs were associated with a low control cost, high control efficacy, and a high potential yield. As expected, the highest EILs were associated with high control costs, lower control efficacy, and lower potential yields. Even with relatively moderate changes in these factors, EILs changed from 2.6 to 3.2 times, depending on life stage.

Several workers have suggested action thresholds for the management of *B. tabaci* in cotton worldwide. Studies in Thailand suggested an action threshold of about two adults per leaf for *B. tabaci* (Mabbett *et al.*, 1980). Populations larger than this were associated with economic damage; however, a definition of what constituted economic damage was not given. Conversely, based on field studies in the Punjab, India, Sukhija *et al.* (1986) recommended that insecticides be applied once populations exceed six to eight adults per leaf from mid-July onwards. Similarly, Stam *et al.*

(1994) suggested an action threshold of six adults per leaf based on their findings in Sudan, which showed that little to no yield loss or stickiness was associated with this density of adult whiteflies. Recent field studies in Arizona (Ellsworth and Meade, 1994) suggested an action threshold between five to ten adults per leaf. Yields and lint quality at these pest levels were high and typical of the area. Results from a regional study in the southwestern U.S. (Nichols *et al.*, 1994) indicate that action thresholds $\leq$ 10 adults per leaf (2.5,5 or 10) give similar pest suppression and yield protection in comparison with untreated plots or those treated once populations exceeded 20 adults per leaf. Finally, Chu *et al.* (1995) suggested action thresholds of 1.2 eggs cm^{-2}, 0.3 nymphs cm^{-2} leaf and 4.1 adults $leaf^{-1}$ based on the maximization of lint yields. Action thresholds for adult *B. tabaci* have been very important in providing producers with guidelines for rational decision-making (e.g. Ellsworth, 1995). For the most part, they are also relatively close to the EILs derived here from an analysis based on economic considerations. This is especially true when variation in population estimates (Naranjo and Flint, 1994, 1995) and the rapid population increases of this insect are taken into account. The close correspondence among all these studies indicates that we are close to defining economically damaging population levels of *B. tabaci*.

The final step to implementing EILs in the field is determination of the economic threshold, which is the pest density at which control should be initiated to prevent populations from exceeding the EIL (Poston *et al.*, 1983; Pedigo *et al.*, 1986). Additional research will be needed to clearly define economic thresholds in relation to our EILs. Because we have determined our EILs in relation to seasonal population density there may be some flexibility in defining the trigger for treatment initiation on any one date. Still, an understanding of the interaction between pest population dynamics and the frequency of sampling will play an important role in determining operational thresholds that will maintain populations of *B. tabaci* below economically damaging levels over the season.

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References

Butler, G. D. Jr and Wilson, F. D. (1986) Whitefly adults in okra-leaf and normal-leaf cottons. *Ariz. Agric. Exp. Stn.* **P–63**, 223–226

Chu, C. C., Henneberry, T. J., Akey, D. H., Naranjo, S. E., Perkins, H. H., Prabhaker, H. and Mackey, B. E. (1995). Sweet-potato whitefly: development of an action threshold for chemical control on cotton. In: *Proceedings of the Beltwide Cotton Conference*, (Ed. by D. J. Herber and D. A. Richter) pp. 873–874. National Cotton Council, Memphis, TN

Chu, C. C., Henneberry, T. J., Weddle, R. C., Natwick, E. T., Carson, J. R., Valenzuela, C., Birdsall, S. L. and Staten, R. T. (1966) Reduction of pink bollworm (Lepidoptera: Gelechiidae) populations in the Imperial Valley, California, following mandatory short-season cotton management systems. *J. Econ. Entomol.* **89**, 175–182

Ellsworth, P., Diehl, J., Dennehy, T. and Naranjo, S. (1994) Sampling sweetpotato whiteflies in cotton. *Cooperative Extension, IPM Series No. 2*, University of Arizona, Tucson. (Revised 1995)

Ellsworth, P. C. (1995) Whitefly sampling, action thresholds and management in Arizona. In: *Proceedings of the Beltwide Cotton Conference* (Ed. by D. J. Herber and D. A. Richter) pp. 101–102. National Cotton Council, Memphis, TN

Ellsworth, P. C. and Meade, D. L. (1994) Action thresholds for whiteflies in Arizona. In: *Proceedings of the Beltwide Cotton Conference* (Ed. by D. J. Herber and D. A. Richter) pp. 878–881. National Cotton Council, Memphis, TN

Flint, H. M., Naranjo, S. E., Leggett, J. E. and Henneberry, T. J. (1996). Cotton water stress, arthropod dynamics, and management of *Bemisia tabaci*. *J. Econ. Entomol.* (in press)

Hector, D. J. and Hodkinson, I. D. (1989) Stickiness in cotton. International Cotton Advisory Committee, *ICAC Rev. Articles, Cotton Prod. Res.* **2**, 1–43

Henneberry, T. J., Hendrix, D. H., Perkins, H. H., Naranjo, S. E., Flint, H. M., Akey, D., Forlow-Jech, L. and Burke, R. A. (1995) *Bemisia argentifolii* (Homoptera: Aleyrodidae) populations and relationships to sticky cotton and cotton yields. *Southwest. Entomol.* **20**, 255–271

Mabbett, T., Nachapong, M. M. and Mekdaeng, J. (1980) The within-canopy distribution of adult cotton whitefly (*Bemisia tabaci* Gennadius) incorporating economic thresholds and meteorological conditions. *Thai J. Agric. Sci.* **13**, 97–108

MSTAT-C (1988) MSTAT-C, a microcomputer program for the design, management, and analysis of agronomic research experiments. Michigan State Univ., East Lansing, MI

Naranjo, S. E. and Flint, H. M. (1994) Spatial distribution of preimaginal *Bemisia tabaci* (Homoptera: Alyerodidae) in cotton and development of fixed-precision sequential sampling plans. *Environ. Entomol.* **23**, 254–266

Naranjo, S. E. and Flint, H. M. (1995) Spatial distribution of adult *Bemisia tabaci* (Homoptera: Alyerodidae) in cotton and development and validation of fixed-precision sampling plans for estimating population density. *Environ. Entomol.* **24**, 261–270

Naranjo, S. E., Flint, H. M. and Henneberry, T. J. (1995) Comparative analysis of selected sampling methods for estimating the abundance of adult *Bemisia tabaci* in cotton. *J. Econ. Entomol.* **88**, 1666–1678

Naranjo, S. E., Flint, H. M. and Henneberry, T. J. (1996) Binomial sampling plans for estimating and classifying population density of adult *Bemisia tabaci* in cotton. *Entomol. Exp. Appl.* **80**, 343–353

Nichols, R. L., Chu, C. C., Ellsworth, P. C., Henneberry, T. J., Naranjo, S. E., Riley, D. G., Toscano, N. C. and Watson, T. F. (1994) Determining an action threshold to prevent whitefly outbreaks. *Phytoparasitica* **22**, 349

Pedigo, L. P., Hutchins, S. H. and Higley L. G. (1986) Economic injury levels in theory and practice. *Annu. Rev. Entomol.* **31**, 341–368

Poston, F. L., Pedigo, L. P. and Welch, S. M. (1983) Economic injury levels: reality and practicality. *Bull. Entomol. Soc. Am.* **29**, 49–53

Prabhaker, N., Toscano, N. C., Perring, T. M., Nuessly, G., Kido, K. and Youngman, R. R. (1992) Resistance monitoring of the sweet-potato whitefly (Homoptera: Aleyrodidae) in the Imperial Valley of California. *J. Econ. Entomol.* **85**, 1063–1068

SAS Institute (1989) *SAS/STAT User's Guide, Version 6*, 4th ed. SAS Institute Inc., Cary, NC

Southwood, T. R. E. and Norton, G. A. (1973) Economic aspects of pest management strategies and decision. *Ecol. Soc. Aust. Mem.* **1**, 168–184

Stam, P. A., Abdelrahman, A. A. and Munir, B. (1994) Comparisons of control and action thresholds for *Heliothis armigera, Bemisia tabaci* and *Aphis gossypii* on cotton in the Sudan Gezira and Rahad regions. *Crop. Prot.* **13**, 503–512

Stern, V. M., Smith, R. F., van den Bosch, R. and Hagen, K. S. (1959) The integrated control concept. *Hilgardia* **29**, 81–101

Sukhija, H. S., Butter, N. S. and Singh, J. (1986) Determination of the economic thresholds of whitefly, *Bemisia tabaci* Genn., on American cotton in the Punjab. *Trop. Pest Manage.* **32**, 134–136, 190, 194

Williams, M. R. (1994) Cotton insect losses, 1993. In: *Proceedings of the Beltwide Cotton Conference* (Ed. by D. J. Herber and D. A. Richter) pp. 743–762. National Cotton Council, Memphis, TN

Williams, M. R. (1995) Cotton insect losses, 1994. In: *Proceedings of the Beltwide Cotton Conference* (Ed. by D. J. Herber and D. A. Richter) pp. 746–757. National Cotton Council, Memphis, TN

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